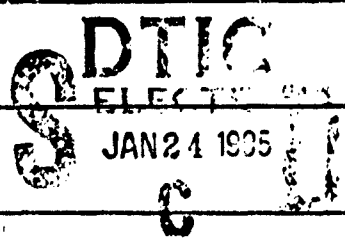


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I. O.

DEVELOPMENT OF THE VANDERBILT COMPTON X-RAY FACILITY

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ABSTRACT

The intense IR photon output of the Vanderbilt FEL is to be made to collide with its own high energy electron beam to create nearly monochromatic Compton Backscattered X-Rays. At Vanderbilt, a sub-project of FEL generated X-Rays is under development parallel to the construction and initial operation of the FEL main project. The electron beamline and IR photon beamline designs are near completion, including design of electron beamline magnets and their layout, design of IR optical beamline elements and their layout, electron and IR optical beam diagnostics and alignment methods.

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DEVELOPMENT OF THE VANDERBILT COMPTON X-RAY FACILITY

INTRODUCTION

When a photon collides with a free electron, its energy and direction change to conserve energy and momentum. This is called the Compton Effect. When the electron is relativistic, that is $\gamma = E/mc^2 \gg 1$ (where E is the total energy of the electron, m the rest mass, and c the speed of light), and the photon has a low energy, that is $\lambda_L \gg \lambda_C = h/mc = 2.42 \times 10^{-12}$ m (where λ_C is the Compton wavelength, h the Planck's constant, λ_L the wavelength of the incident photon), then the wavelength of the scattered photon is given by the formula

$$\lambda_s = \lambda_L (1 + \gamma^2 \theta^2) / 4 \gamma^2 \quad (1)$$

where θ is the angle through which the electron is scattered. For an infrared photon with a $2 \mu\text{m}$ wavelength scattered in the backward direction ($\theta = 180^\circ$) off a 43 MeV electron, the wavelength of the scattered photon is 0.7 \AA , which corresponds to an X-ray with an energy of 17.6 keV, in the X-ray part of the spectrum. Since intense, monochromatic light can conveniently be generated by lasers, and an intense monochromatic electron beam can be generated by conventional accelerators, X-rays produced by Compton scattering can be made quite monochromatic as compared with those generated by conventional X-ray tubes. Such narrow-spectrum X-rays may have important advantages for medical imaging. In particular, the low-energy photons from a conventional X-ray tube are absorbed close to the skin surface in the patient and contribute to the patient's X ray dose, but not to the X-ray image. High energy X-rays, on the other hand, often pass through the patient undergoing scattering which tends to fog the film, and degrade the X-ray image. It is the intermediate X-rays which experience absorption in the body due to photoelectric processes, and form the X-ray image. For mammography, the useful X-rays are those with wavelengths around 0.7 \AA and energies around 18 keV. By using X-rays of this energy and its improved contrast, it is

estimated that the patient dose required to provide the image quality of a standard mammogram can be reduced by a factor of about 50.

In the Vanderbilt Compton X-ray facility, infrared photons at wavelengths around $2\text{ }\mu\text{m}$ are produced by the Vanderbilt free-electron laser, while electrons at energies around 43 MeV are provided by the beam emerging from the free-electron laser. These are collided in a small interaction region, about $40\text{ }\mu\text{m}$ in diameter, to produce X ray photons of the desired wavelength at the rate of about 10^{10} per second. The schematic of this project is shown in Fig.1. These X-rays can be used to explore the use of such photons in medical imaging of breast cancer, and eventually, to perform mammography in clinical trials.

INTERACTION GEOMETRY

Since the expected emittance of the electron beam is smaller than the laser wavelength, the emittance may be ignored in optimizing the interaction geometry. Only the electron pulse length need be considered, so we optimize by setting the Rayleigh range $\approx 1/2$ the electron pulse length ($\approx 1/2$ of the optical wavelength).

The design electron energy of the Vanderbilt FEL is 43 MeV and the infrared optical wavelength is about $2\text{ }\mu\text{m}$. Under these conditions, the X-ray wavelength is $0.7\text{ }\text{\AA}$. For an average laser power of 6 W and an average electron beam current of 200 mA, the optimized X ray photon output is 4.0×10^{12} per second per steradian; the electron beam and the infrared beam are both focused to the same size, $12\text{ }\mu\text{m}$ in radius. Both beams in the interaction zone are shown in Fig.2. For experimental convenience, the beams will be focused to a larger spot, about $20\text{ }\mu\text{m}$ in radius. The number of output photons is then 2.7×10^{12} per second per steradian.

ELECTRON BEAMLINE DESIGN

Since Compton X-rays are generated along the direction of the the electron beamline, and the X-ray laboratory is one floor above the FEL vault, we must either bend the electron beam from its original horizontal direction, into the direction of the laboratory, or generate X-rays along the

original electron direction, and bend the X-rays up to the laboratory. This option, opened up by recent technological developments in X-ray "fiber optics", is discussed later.

The electron beamline design shown in Fig.3 is used to deflect the electron beam up toward the laboratory, so that the X-rays are produced in that direction. After passing through the interaction region, the electrons are directed back to the original beamline and transported to the beam dump.

The beamline design is complicated by the finite emittance and energy spread of the electron beam. A further complication of a practical nature is introduced by the fact that the electron beamline lies in a plane tilted about 47° from the horizontal plane. Because the electron beam has an energy spread of the order of a few percent after emerging from the wiggler, the beam transport system used to focus the beam into the interaction region must be achromatic. Our design is to make four identical bends, each consists of two 20° single bends with a quadrupole in between the two dipoles, together they make an "achromatic bend". Other quadrupoles are needed for focusing and beam-control purposes. A total of eight 20° dipole bending magnets and fifteen quadrupoles are needed for this design. First and second order TRANSPORT and POISSON calculations were used in the design.

Because the emittance of the electron beam is expected to be smaller than the wavelength of the laser, the emittance allows the electron beam to be focused inside the interaction region. However, the emittance affects the monochromatic quality in the following way, within the interaction cone of each electron, the wavelength increases with the angle from the electron direction according to the formula (valid for $\gamma \gg 1$)

$$\lambda = \lambda_0 (1 + \gamma^2 \theta^2), \quad (2)$$

where θ is the angle between the direction of the radiation and the electron motion, λ_0 is the photon wavelength in the forward direction. Thus, if the electrons are not moving parallel to each other, the X-radiation in a given direction will contain a spread of wavelengths. A further spread in the X-ray wavelength is caused by the energy spread of the beam. To minimize this effect, it is

important that the electron beamline not expand the emittance by converting the electron energy spread into emittance growth.

AN ALTERNATIVE ELECTRON BEAMLINE DESIGN

Recently, a new kind of X-ray optics, X-ray "capillary", or X-ray "fiber optics" is under consideration [1]. It uses multiple tiny hollow glass tubes. X-rays undergo myriad glancing incidence total external reflections inside the tubes with only limited loss. With these capillaries we will be able to first collimate, then bend the X-rays up to the X-ray laboratory. The schematic of this design is shown in Fig.4.

With capillary technology, we can avoid having to build a complicated electron beamline with many magnets in order to bend the electrons. This approach will simplify the whole electron beamline design and enable us to use fewer magnets. Another advantage of this design will be to avoid sending the electrons in the direction of the X-ray laboratory where people will be working, thus reducing the potential radiation hazard. The disadvantage of this design is that the capillary technology has not yet been actually used as a scientific research tool, making success uncertain. The cost of a capillary tube bundle device and a few magnets is estimated to be less than the total cost of the magnets needed in the first design.

OPTICAL BEAMLINE DESIGNS

The purpose of the infrared beamline is to transport the FEL infrared optical beam to the interaction region and focus it at the "interaction zone" to a diameter of about 40 μm . When the electron and laser beams are not exactly collinear, the wavelength shifts slightly according to the formula

$$\lambda = \lambda_c / \cos^2 \theta \quad (3)$$

where θ is the angle between the axes of the electron and laser beams, λ_c the wavelength in the collinear case. The angular factor for the produced X-ray beam intensity of the crossing beams is

also $\cos^2 \theta$. This is a small effect for small angles, and it is therefore possible to use geometries in which the beams cross at a small angle. However, if the angle becomes much larger than the convergence angle of the laser beam, the electrons have less time to interact with the laser beam and this reduces the X-ray intensity. Therefore, at the region beyond the interaction zone, all three beams have to overlap geometrically. However, passing the electron beam through any optics transporting the infrared beam is not possible without damaging the optics. Also, the X-ray beam has to be transported through this system to go into the laboratory upstairs. These conditions complicate the infrared beamline design. Four approaches for solving these problems are under consideration:

1) The first approach is to transport the infrared beam collinearly with the electron beam. This is shown in Fig.5, corresponding to the $\theta = 0$ case. The mirror that reflects the infrared beam has a hole at the center, which is also the center of the beamline, large enough to let the electron beam and the accompanying X-rays pass through. The advantage of this method is that it is simple and inexpensive. The disadvantage is loss and distortion of the infrared beam due to the hole in the middle. This causes a loss of the most intense portion of a Gaussian infrared beam. The total loss due to the hole alone is estimated to be 1% of the beam intensity, if we use a 10 mm radius mirror with a 1 mm radius hole placed at 30 cm from the interaction zone. Also, there will be some electrons on the edge of the beam "scraping" the mirror near the hole, which will cause damage to the mirror.

One solution to the intensity loss is to place the hole off center in a region of lower intensity. However, this will make the two beams non-collinear, as shown in Fig.5, for the $\theta \neq 0$ case, and reduce the interaction between the beams. The estimated loss due to the angular factor and the intensity loss is 0.7% of the beam intensity, assuming the hole is mounted to the $1/e$ intensity point of the the infrared beam 30 cm away from the interaction zone.

2) The second approach is an alternative to the first method, replacing the standard mirror for transporting the infrared beam with a beryllium mirror. This mirror can be placed further downstream after the electron beam is directed away. This is (an alternative way for the first

method too) shown in Fig.6. The difference is that this Beryllium mirror is almost transparent to the X-rays and can be coated to reflect infrared photons. Therefore, the use of a Beryllium mirror does not introduce the distortion to the beam because this avoids the need for placing any hole on the mirror.

3) The third approach is to make the infrared beam and the electron beam cross initially with a small angle. This is shown in Fig.7. The reduced X ray output due to the angular factor is estimated to be 0.1%. This is the simplest, most effective and least expensive design of all. It avoids the serious electron damage problem of the first approach.

4) The fourth approach is shown in Fig.8. An axicon pair is used to reshape the infrared beam to a hollow one [2]. The hole necessary for the electrons and X ray photons to pass through can be adjusted to the desired size and placed where the beam itself is hollow. The disadvantage of this approach is the cost and complexity of the axicon pair.

ELECTRON BEAM DIAGNOSTICS AT FOCUS

To optimize the Compton X ray output, the electron beam and the infrared optical beam must be aligned collinearly and focused at a common point of about 20 μm radius. Aligning the system and diagnostics for both beams are necessary. The difficulties for the diagnostics are:

First, at the focus, our electron beam has the luminosity of $4.5 \times 10^7 \text{ W/m}^2$. This is more than enough to melt any screen material in a single macropulse.

Second, both beams have a pulsed structure. Thus not only must both beams be aligned and focused spatially, but also the picosecond micropulses of both beams must meet simultaneously at the focus.

Of these, the first problem is the most difficult one to deal with. The most straightforward and most reliable method for diagnosing an electron beam with a beam size as small as tens of micrometers is to have a screen at the focusing point. To avoid melting diagnostic screens, when diagnosing, we must reduce the electron beam intensity. Beam intensity can be reduced by one of the several ways:

1) The first method is to place a slab with the proper thickness and material, an "attenuator" in the electron beam, at the upstream end of the interaction region so that the multiple scattering processes reduce the number of electrons as shown in Fig.9. Electrons coming out of this attenuator with the "wrong" energy and emittance can be filtered out with a pair of "emittance filters" in each plane and an "energy filter". The latter already exists for the FEL itself. The former can be inserted into the beamline without too much difficulty. Computer simulation with the program EGS4 assures us of the effectiveness of the method and the requirements for the attenuator material.

An alternative method is to place holes in the slab, to form a "pepper pot". The holes allow the desired portion of electrons to go through the attenuator without being disturbed. The emittance filters and the energy filter again filter out the "wrong" electrons scattered by the slab. This is also shown in Fig.9.

2) The second method is to scan the electron beam on the diagnostic screen at the focus with an RF cavity in the horizontal or vertical plane. Instead of having an "image spot" of the electron beam, we get two crossed lines. The width of the horizontal line represents the electron beam size vertically. The width of the vertical line represents the beam size horizontally, as shown in Fig.10. The method is more expensive than the attenuator, even though we can make use of the existing RF source.

3) The third method can be called the "non-interactive" method. It works under the same principle that the Compton X-ray production works. The RF from the same source as the FEL, which has a frequency of 2856 MHz, is guided into the interaction zone where it collides with the electron beam. A light beam of about $3.7 \mu\text{m}$ in wavelength will be generated as a "probe beam", as shown in Fig.11. The probe beam goes through the same optical elements as the infrared beam does so that the alignment of the both beams can be done simultaneously with the same screen.

CONCLUSION

At Vanderbilt, tunable, near monochromatic Compton X-rays will be generated using the FEL residual electrons and the FEL output infrared optical beam. The project is near its construction stage. A few of the possible designs for different parts of beamlines are reported here, including the electron-beam design, the infrared optical-beam design, electron beam diagnostics and a possible X-ray optical design using capillary "fiber optics".

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- [2] Golub and R. Treblay, Optical Society of America (1990) 1264

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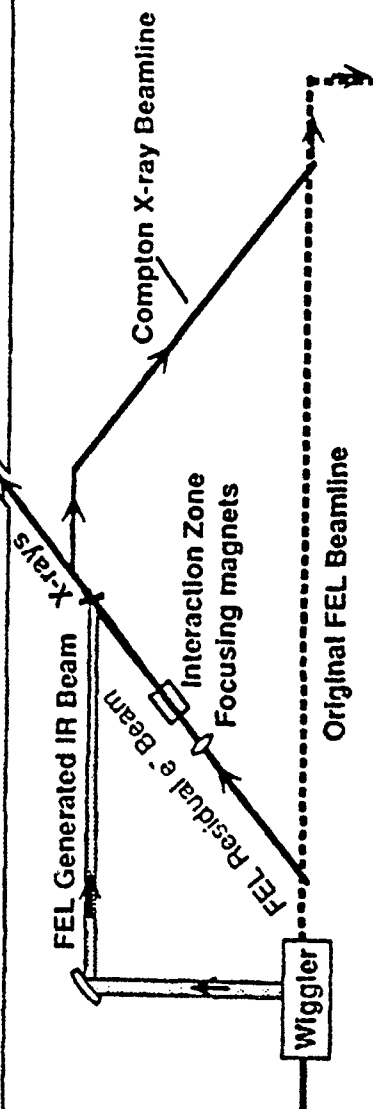
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VANDERBILT MFEL COMPTON X-RAY PROJECT

Near monochromatic X-rays are generated by the backscatter of FEL produced IR photons through head on collision with the FEL residual electrons.

X-ray Lab

concrete floor

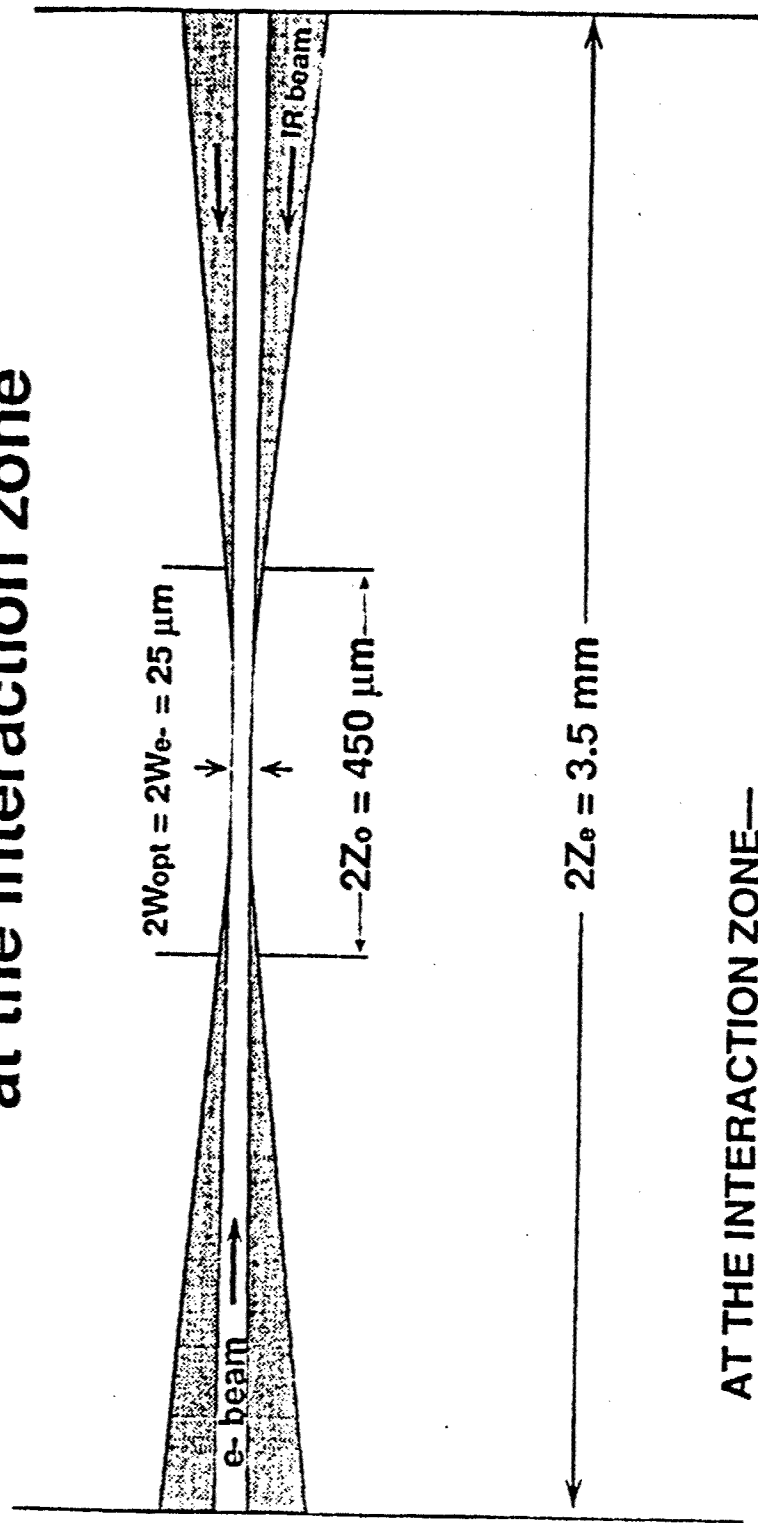


Beam Dump

Fig. 1

Earth

Optimized e⁻ beam and IR beam at the interaction zone



AT THE INTERACTION ZONE—

Both the IR beam and the e⁻ beam need to be focused to a small waist to get optimized x-ray photons.

Fig. 2

e^- BEAMLINE LAYOUT

The e^- beamline bends the e^- beam to the direction of the X-ray lab and then back to the e^- beam dump.

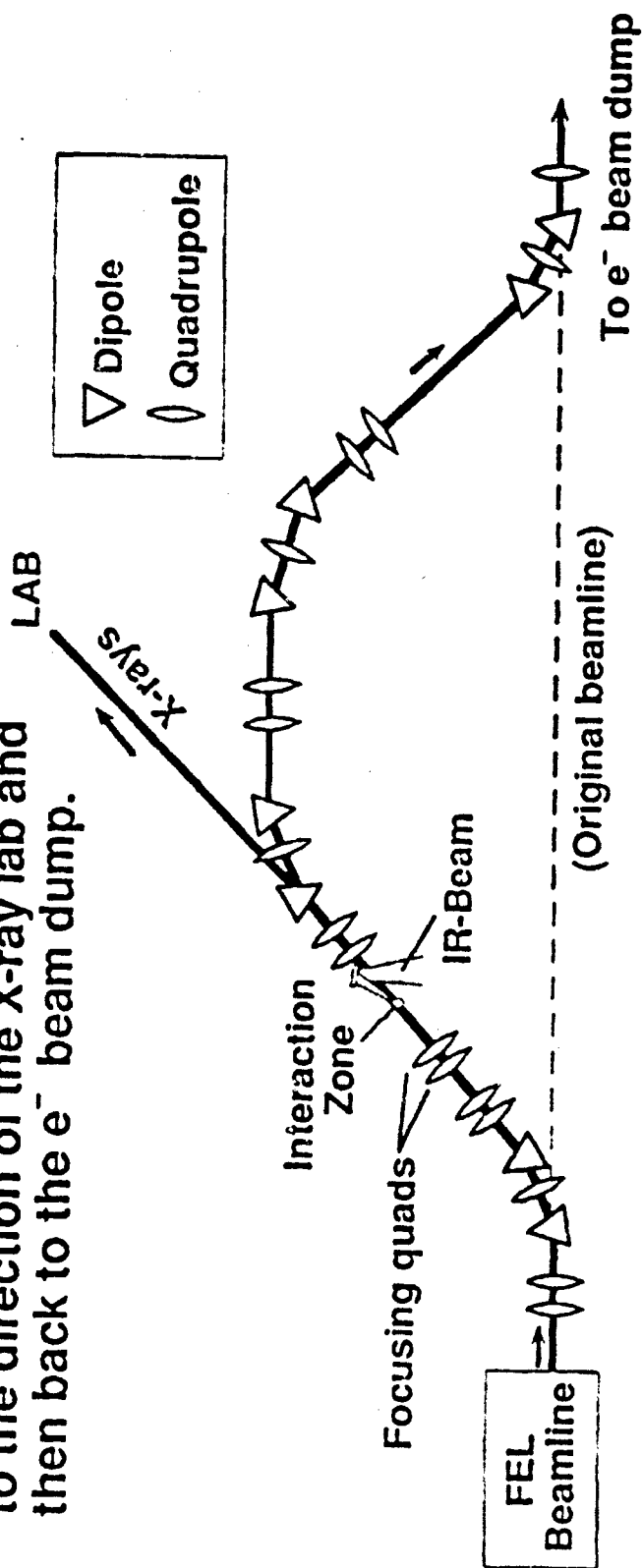


Fig. 3

AN ALTERNATIVE ELECTRON BEAM DESIGN

A new commercial technology makes it possible to bend the x-rays up to the lab using x-ray "fiber optics".

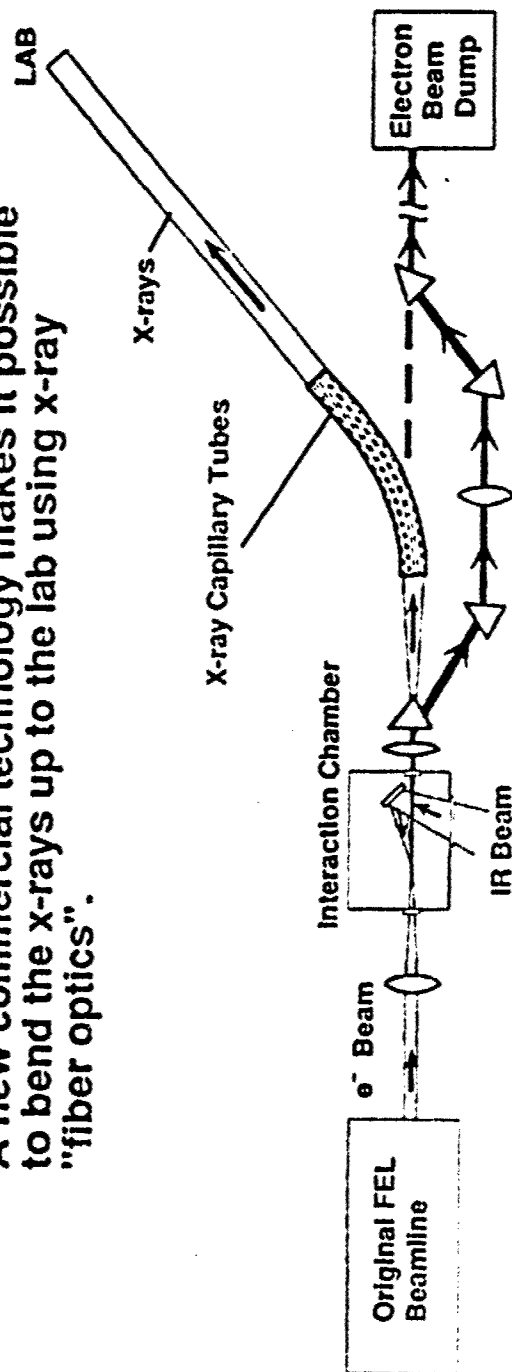


Fig. 4

IR BEAM FOCUSING DESIGNS

Placing a hole in the reflecting mirror reduces the intensity of the IR beam, but this avoids the use of a Be mirror.

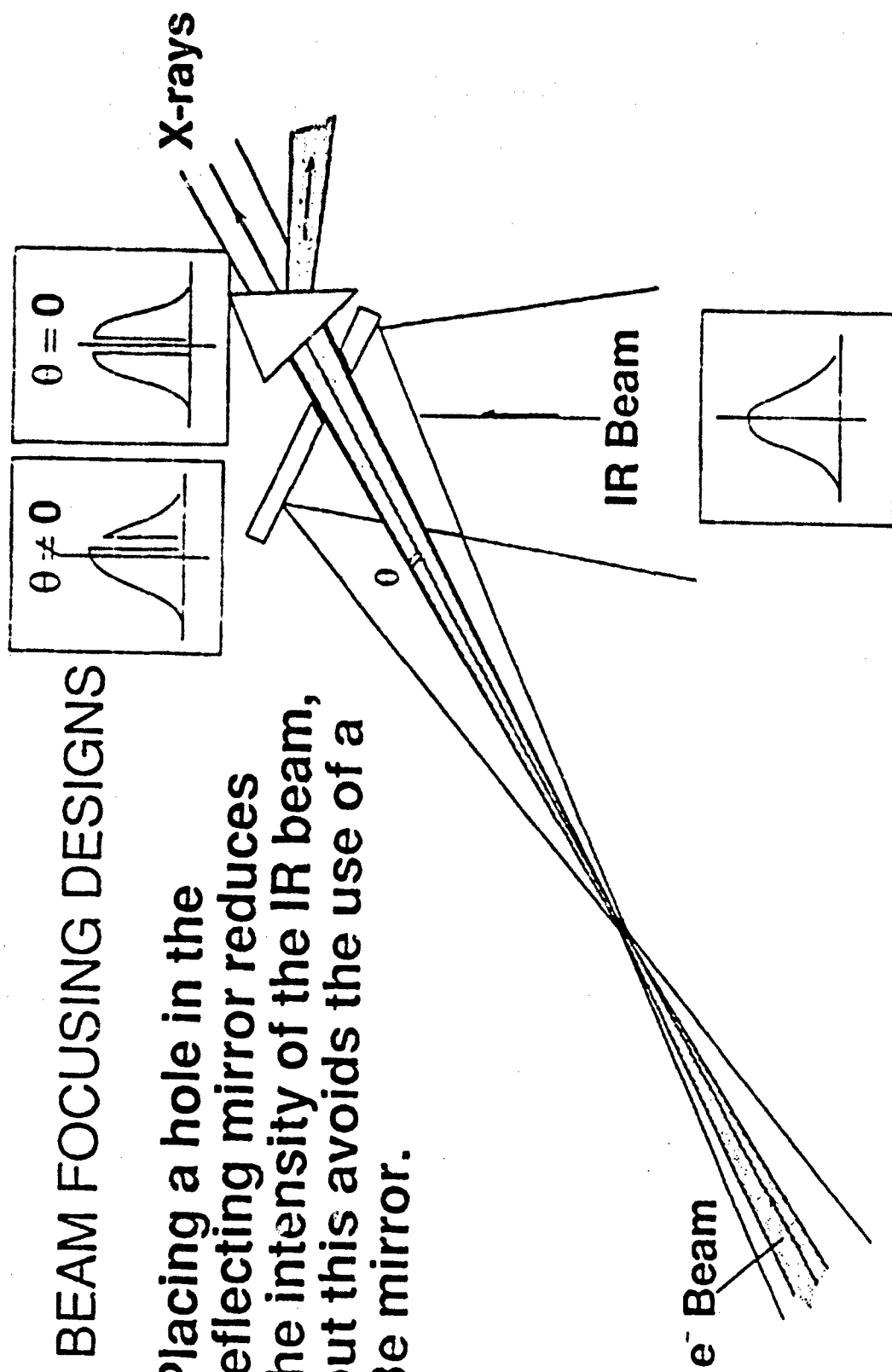


Fig. 5

IR BEAM FOCUSING DESIGNS

The use of a Be mirror allows us to focus the IR beam collinearly with the e^- beam and to let the e^- beam and X-rays go through, but Be mirrors are hard to fabricate.

(Correction: The Be mirror should have been placed beyond the dipole.)

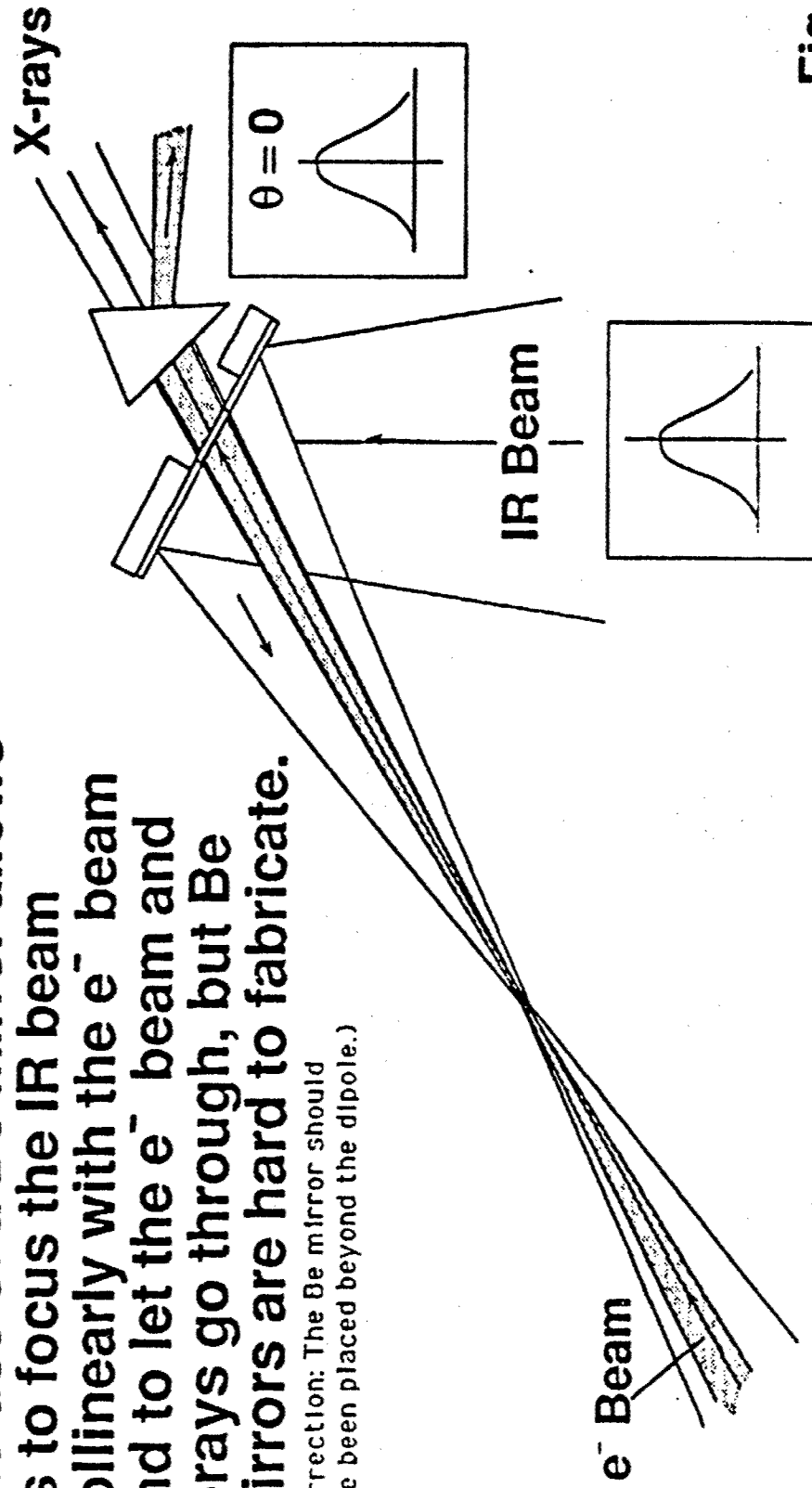


Fig. 6

IR BEAM FOCUSING DESIGNS

Focusing the IR beam non-collinearly with the e^- beam with a single mirror makes the simplest design, but reduces the beam intensity, but reduces the interacting length.

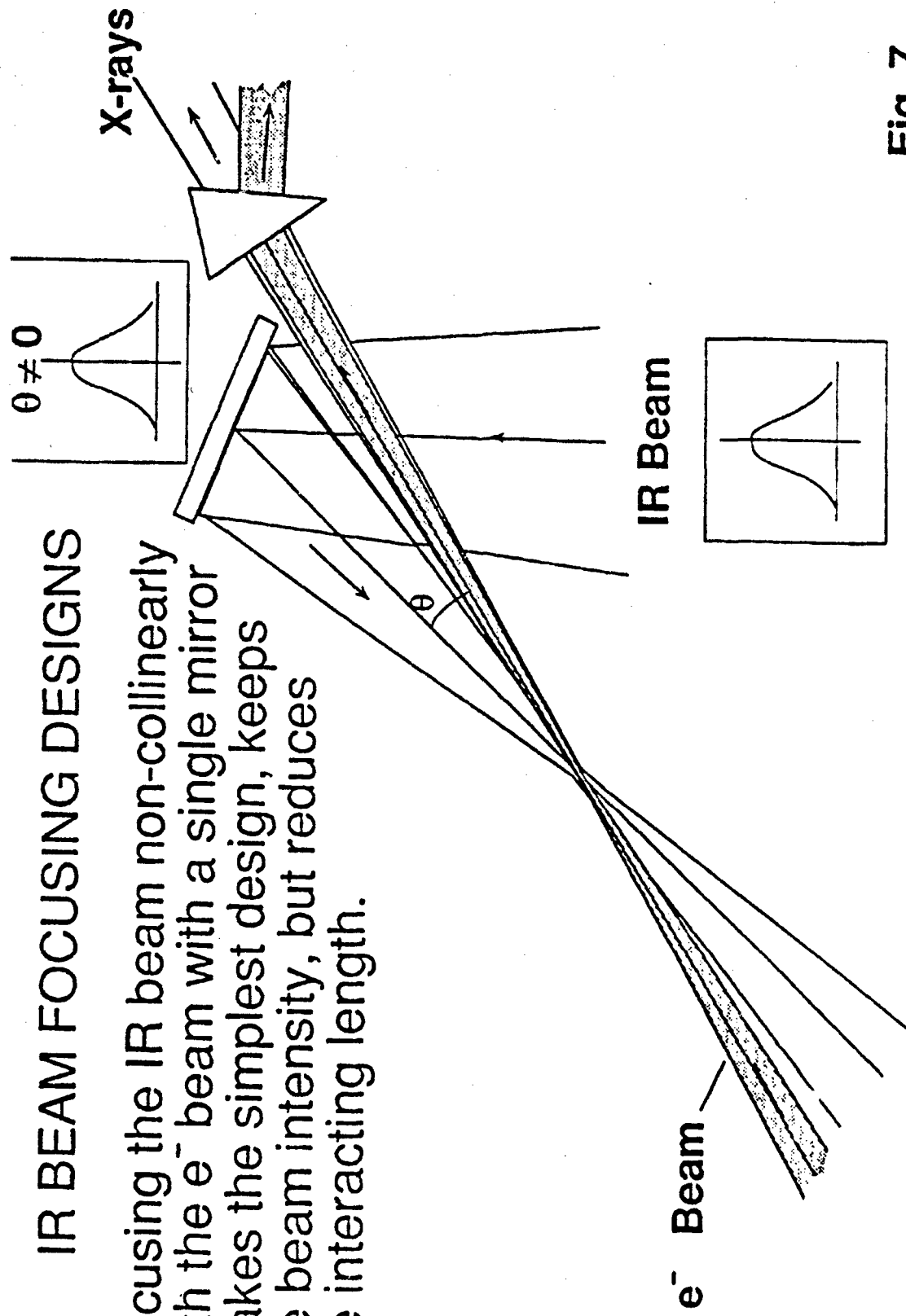
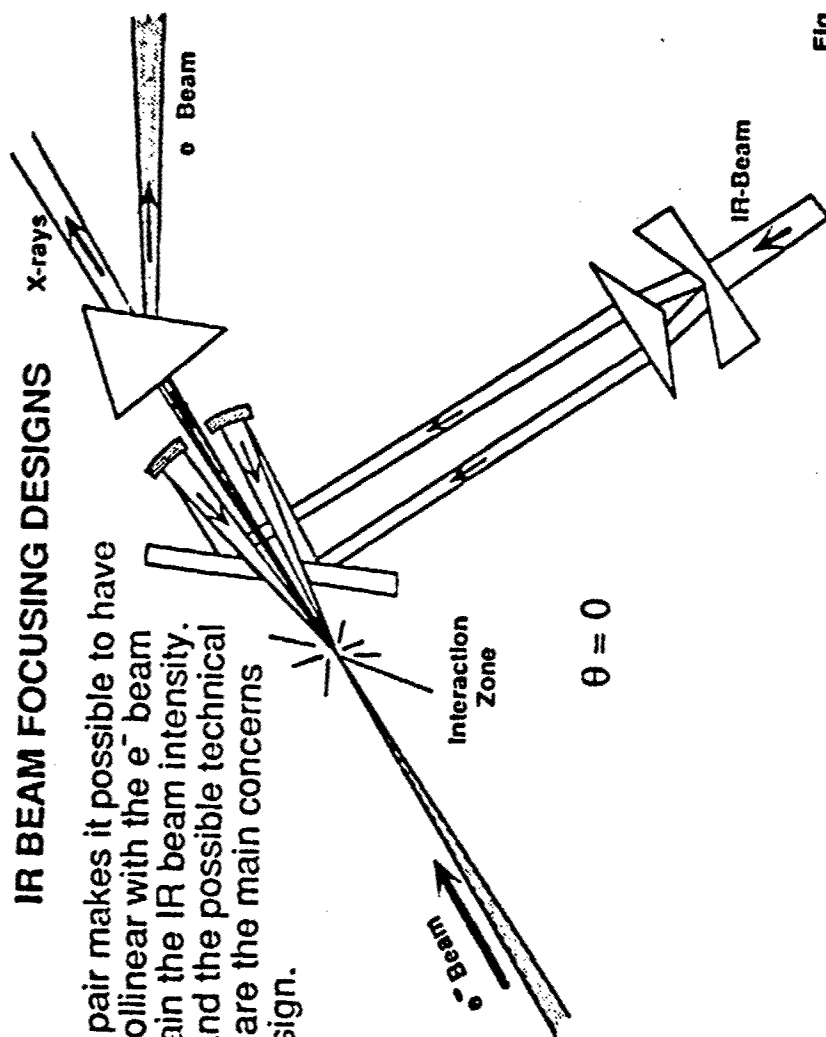


Fig. 7

IR BEAM FOCUSING DESIGNS

An axicon pair makes it possible to have IR beam collinear with the e^- beam and maintain the IR beam intensity. The cost and the possible technical difficulties are the main concerns for this design.



ELECTRON BEAM DIAGNOSTICS

- (a) A block or a "pepper pot" is used to attenuate the electron number in each micropulse to avoid melting the diagnostic screen at the tightly focused "interaction zone". The "emittance filters" and the "energy filter" are used to keep the beam properties the same with or without the attenuator.

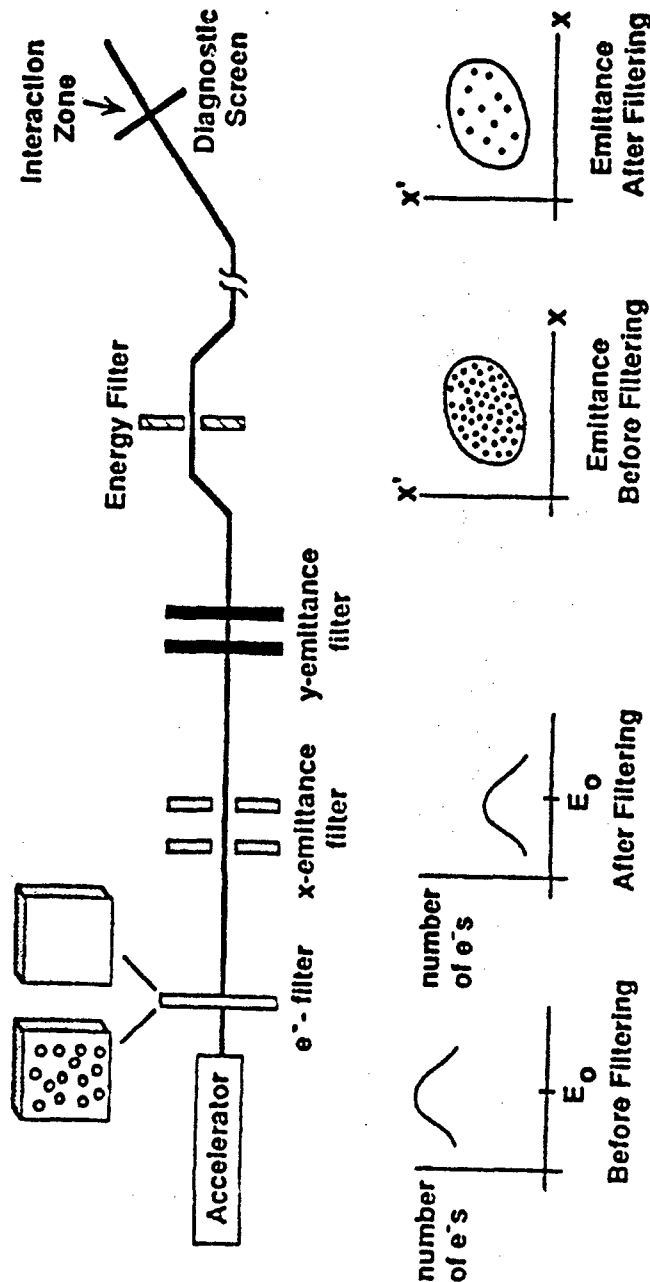


Fig. 9

ELECTRON BEAM DIAGNOSTICS

- (b) "Sweeping" the e^- beam makes it possible to measure the beam dimensions and reduce the number of e^- hitting the diagnostic screen.

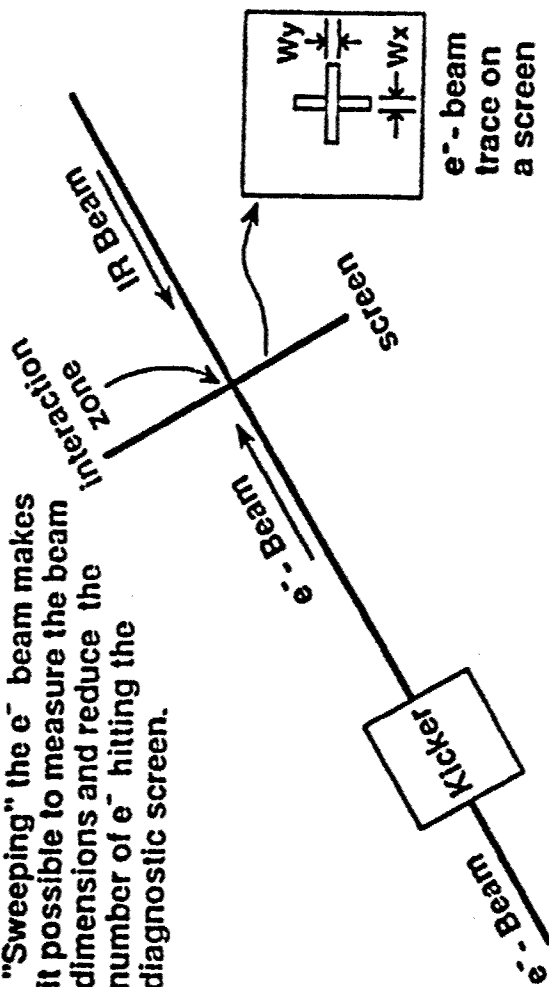


Fig. 10

ELECTRON BEAM DIAGNOSTICS

- (c) An RF generated "probe" beam goes through the same optics with the IR beam. This makes it possible to diagnose the alignment of the e^- beam and the IR beam.

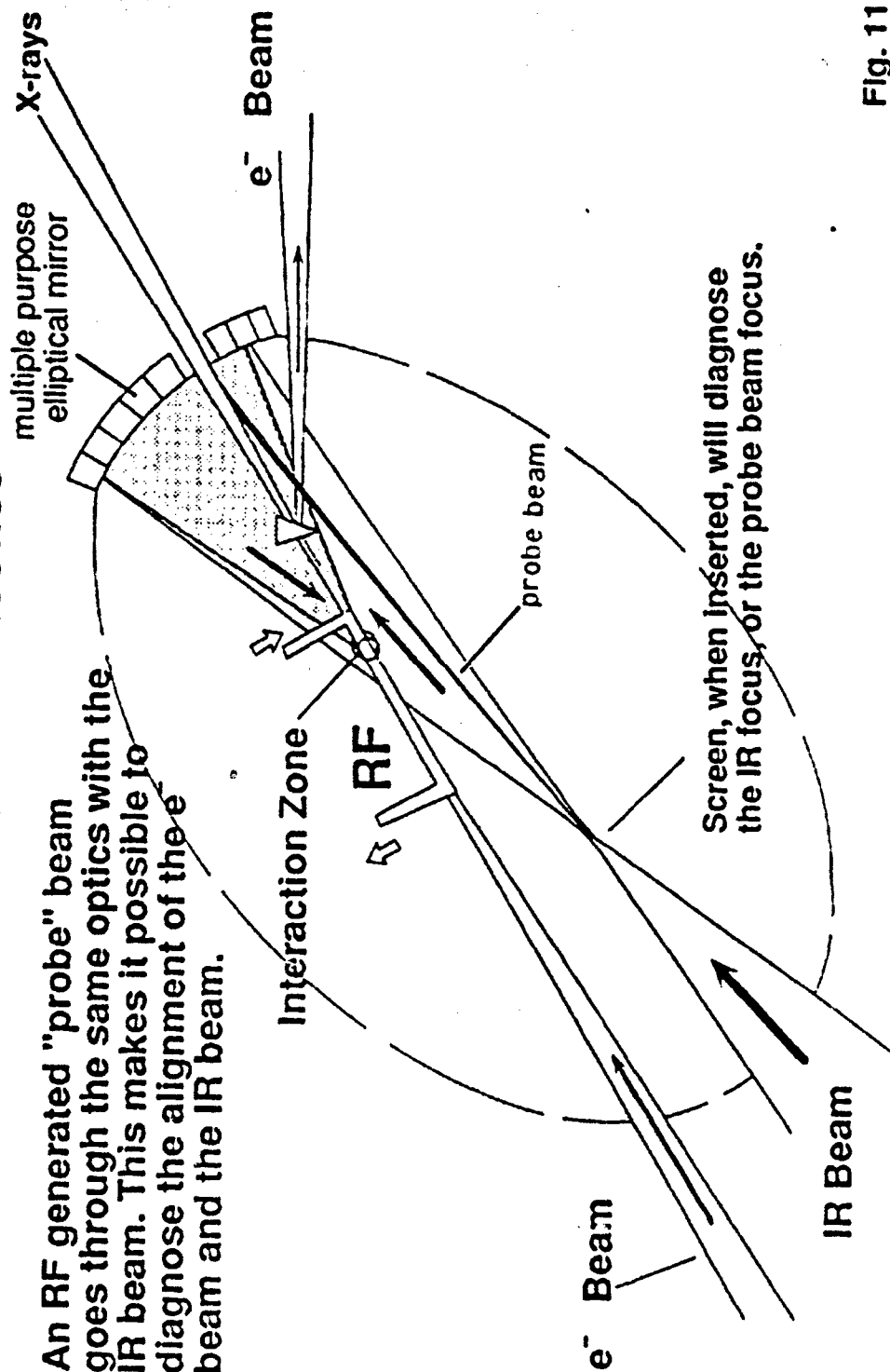


Fig. 11